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EVALUATION OF BOND TESTING EQUIPMENT FOR INSPECTION OF ARMY ADVANCED COMPOSITE AIRFRAME STRUCTURES

October 1988

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ABSTRACT

Forty-one ultrasonic bond testing instruments for nondestructive inspection of composite airframe structures were evaluated based on information available in the literature. In addition, three of these instruments, the Fokker Bondtester Model 80-L, the BondaScope 2100, and the Sonatest UFD-S, were evaluated in the laboratory using ten specimens of composite airframe structures supplied by the Army. All the specimens had unknown flaw conditions. Both the Fokker Bondtester and the BondaScope required only a few hours of operator training in calibration and operation. Both instruments require a liquid couplant and are used for spot checking. The UFD-S instrument was difficult to set up and calibrate without reference samples of known characteristics. Also, extensive operator training is required to calibrate and operate the UFD-S instrument. The UFD-S uses a wheel probe which does not require a liquid couplant and allows continuous scanning of the specimen. The inspection speed of the UFD-S was therefore much greater than that of the other two instruments. Surface roughness, surface curvature, and variations in paint thickness were observed to limit the applicability of the instruments. Although these instruments have certain limitations, they are suitable for routine field inspection of composite airframe structures.

PREFACE

This program was performed as a special task by the Nondestructive Testing Information Analysis Center at Southwest Research Institute under Contract No. DLA 900-84-C-0910, Mod. P00070 for SLCMT-MRM, U.S. Army Materials Technology Laboratory, Watertown, Massachusetts. The program was conducted under the technical direction of Mr. Paul G. Kenny of SLCMT-MSI-NE. The authors wish to thank the following individuals for their cooperation in providing the ultrasonic bond testing equipment used in the program: Mr. Ronald J. Botsco of NDT Instruments, Inc.; Mr. Jim Rhamey of Automation/Sperry, Qualcorp; Mr. Paul Slaba of NDT Technologies U.S., Inc.; Mr. Jerry Slaba of NDT Technologies, Inc.; and Mr. Gordon Turner of NDT Equipment and Supply, Inc.

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SUMMARY

Forty-one ultrasonic bond testing instruments for nondestructive inspection of composite airframe structures were evaluated based on information available in the literature. Three of these instruments, the Fokker Bondtester Model 80-L, the BondaScope 2100, and the Sonatest UFD-S, were evaluated in the laboratory using ten specimens of composite airframe structures supplied by the Army. All the specimens had unknown flaw conditions. Both the Fokker Bondtester and the BondaScope required only a few hours of operator training in calibration and operation. Both instruments require a liquid couplant and are used for spot checking. The UFD-S instrument was difficult to set up and calibrate without reference samples of known characteristics. Also, extensive operator training is required to calibrate and operate the UFD-S instrument. The UFD-S uses a wheel probe which does not require a liquid couplant and allows continuous scanning of the specimen. The inspection speed of the UFD-S was therefore much greater than that of the other two instruments. Surface roughness, surface curvature, and variations in paint thickness were observed to limit the applicability of the instruments. Although these instruments have certain limitations, they are suitable for routine field inspection of composite airframe structures.

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I. INTRODUCTION

A. Background

Advanced composite materials are finding widespread application in the construction of Army helicopters, ranging from the fabrication of secondary structures to the construction of primary load-carrying airframe structures.

Composite airframe structures are fabricated by adhesively bonding the components together. During service, flaws such as debonds, delaminations, and cracks may be induced in a structure by overstress and impact. If such flaws go undetected and are allowed to grow, they will eventually cause serious weakening and failure of the structure. To ensure the reliability and safety of a structure, it is therefore necessary to inspect the structure regularly for flaws and damages.

In the nondestructive inspection of advanced composite airframe structures, ultrasonic techniques such as through-transmission, pulse-echo, and resonance are extensively used. Ultrasonic bond testing instruments are essential equipment for the inspection. A variety of ultrasonic bond testing instruments are presently available on the market for inspection of composite structures. For determining the Army's future equipment needs to improve the accuracy and reliability of nondestructive inspection of Army advanced composite airframe structures, information on the capabilities and limitations of these commercial ultrasonic instruments is prerequisite. The goal of the program reported herein was to obtain updated information on the capabilities of commercially available ultrasonic bond testing equipment.

B. Objective

The specific objective of the program was to identify and evaluate commercially available ultrasonic bond testing instruments for inspection of adhesively bonded composite airframe structures. To effectively utilize Army funds, the objective of the program was to be accomplished by expanding an Air Force program entitled "Through-Transmission/Pulse-Echo Ultrasonic Equipment Evaluation."*

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*The Air Force program was conducted for the Nondestructive Inspection Program Office, Service Engineering Division, Directorate of Material Management and Engineering Inspection, San Antonio Air Logistics Center, Kelly Air Force Base, San Antonio, Texas 78241, as a special task by the Nondestructive Testing Information Analysis Center (NTIAC) under Contract No. DLA 900-84-C-0910, CLIN 0001BC. The program was completed in September 1987, and a copy of the final report can be obtained from the Defense Technical Information Center, Cameron Station, Alexandria, Virginia 22314.

C. Scope of Work

The scope of work of the subject program included:

(1) Literature evaluation of the capabilities of commercial ultrasonic bond testing instruments identified during the Air Force program. The evaluation was to be based solely on the information available in the literature collected during the Air Force program.

(2) Laboratory testing and evaluation of three instruments selected during the Air Force program by using samples of composite airframe structures supplied by the Army.

II. LITERATURE EVALUATION OF ULTRASONIC BOND TESTING EQUIPMENT FOR INSPECTION OF COMPOSITE AIRCRAFT STRUCTURES

During the course of the Air Force program, more than fifty ultrasonic bond testing instruments were identified, as listed in Appendix A. Of these, forty-one instruments were evaluated based on the data available in the literature including product brochures and catalogues obtained from equipment manufacturers or distributors. The parameters considered in the evaluation included flaw sensitivity, accuracy in flaw location, dependency on operator skill, need for surface preparation, inspection speed, repeatability and reliability of inspection results, portability, maintainability, power requirements, personnel safety, and equipment cost. The evaluation form and the rating guidelines used are given in Appendix B. The overall findings are summarized in Table 1. Because of inadequate information, some of the parameters used such as accuracy, sensitivity, repeatability, and reliability were difficult to determine quantitatively. As a result, the evaluation was qualitative and, in some cases, incomplete. Therefore, no attempts were made to rank the instruments.

The majority (32 out of 41) of the evaluated instruments were based on the conventional pulse-echo/through-transmission techniques. Of the remaining nonconventional ultrasonic instruments (9 out of 41), six were based on resonance techniques, two on the acousto-ultrasonic technique, and one on the shadow technique (see Section III.A.2). All the instruments required some degree of operator skill and experience, particularly in interpretation of the detected signals.

Most of the instruments (33 out of 41) used sensors (or probes) which require a liquid couplant such as light machine oil or water to transmit ultrasonic energy through the contacting interfaces between the probe and the part under inspection. Several instruments (8 out of 41) were operated with dry-coupled probes which do not require a liquid couplant. The dry-coupled probes use a pliable and resilient material such as rubber to transfer ultrasonic energy from the piezoelectric crystal to the part under inspection and vice versa. The coupling state of both the liquid-coupled and dry-coupled probes influences the inspection results. Therefore, to obtain repeatable results, uniform and consistent coupling of the probes is required.

Almost all the instruments (38 out of 41) evaluated required a smooth and clean surface of the part for inspection. However, substantial surface preparation such as removing paint on the part is not generally required. In addition, most of the instruments (36 out of 41) were operable in field environmental conditions. Except for highly sophisticated and automatic instruments and some instruments operated with a wheel-type probe, the inspection speed of the instruments was slow (32 out of 41).

With the recent advancements in semiconductor and computer technologies, ultrasonic NDT instruments have been undergoing a transition from analog and manual types to digital, automatic, and computer-controlled types. Most of the instruments for which information was gathered (34 out of 41) incorporated the recent, state- of-the-art electronic design technologies partially or totally. At present, almost all instruments (37 out of 41) are equipped with visual and/or audible alarm to aid in flaw detection. The majority of the instruments

Table 1

SUMMARY OF LITERATURE EVALUATION OF ULTRASONIC INSTRUMENTS FOR NONDESTRUCTIVE INSPECTION OF BONDED STRUCTURES*

	Instrument	Technique	Operation Skill Setup	Operation Skill Proc.	Operation Skill Interp.	Need for Liquid Couplant	Need for Surface Preparation	Sensitivity to Environment	Inspection Speed	Repeatability	Recorder Interface Availability	Portability	Power Rqmt.	Maintain-ability	Equipment Cost	Personal Safety	Ability to Automate
1.	Ultra Image III	PE/TT(1)	High	High	Low	Yes	Mod	Low	High	High	High	Mod	High	Mod-Low	High	High	Automated
2.	Acous.-Ultrasonic Instru Sys	AU(2)	High	High	High	Yes	Mod	Mod	Low	Low	Mod	Mod	High	Mod-Low	High	High	High
3.	Multisonic/PC	PE/TT	High	High	Low	Yes	Mod	Mod	High	High	High	Low	High	Mod-Low	High	High	Automated
4.	UFD-S	Shadow	Low	Low	Low	No	Low	Low	Mod	Mod	Mod	High	Low	Mod	Mod	High	Low
5.	ZIPSCAN 2	PE/TT	High	High	Low	Yes	Mod	Low-Mod	High	High	High	Mod	High	Mod-Low	High	High	Automated
6.	TTU-90	PE/TT	Low	Low	Mod	No	Low	Low	Mod	Mod	Mod	High	Mod	Mod	Low	High	Mod
7.	USIP 12	PE/TT	Mod	Mod	Mod	Yes	Mod	Low	Low	Mod	Mod	Mod	Mod	Mod	Mod	High	Mod
8.	USIP 11	PE/TT	Low	Low	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Mod	Mod	Low	High	Low
9.	PARIS	PE/TT	High	High	Mod	No	Mod	Low	High	High	High	Mod	High	Mod-Low	High	High	Automated
10.	Sigma Series 2000	PE/TT	High	High	Mod	Yes	Mod	Mod	High	High	High	Low	High	Mod-Low	High	High	Automated
11.	USD-1	PE/TT	High	High	Mod	Yes	Mod	Low-Mod	Low	High	High	Mod	High	Mod-Low	High	High	Automated
12.	Fokker Bondtester Model 80L	Reson.	Low	Low	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Low	Mod	Mod	High	High
13.	Metrotek M-Series	PE/TT	Low	Mod	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Mod	High-Mod	Mod	High	Mod
14.	NDT 132	PE/TT	Low	Mod	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Low	High-Mod	Low	High	Mod
15.	AET 206AU	AU	Mod	Mod	High	No	Low	Low	Mod	Mod	Mod	High	Low	High-Mod	Mod	High	Mod
16.	NovaScope 3000	PE/TT	Low	Low	Low	Yes	Mod	Low	Low	Mod	Mod	High	Low	Mod	Low	High	Mod
17.	NovaScope(3)	PE/TT	Low	Low	Low	Yes	Mod	Low	Low	Mod	Mod	High	Low	Mod	Low	High	Mod
18.	BondaScope 2100	Reson.	Low	Low	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Mod	Mod	Mod	High	High
19.	210 Bondtester	Reson.	Low	Low	Mod	No	Mod	Low	Low	Mod	Mod	High	Mod	Mod	Low	High	Mod
20.	S-1A Sondicator(3)	Reson.	Low	Low	Mod	No	Mod	Low	Low	Mod	Mod	High	Low	Mod	Mod	High	Mod
21.	S-2B Sondicator	Reson.	Low	Low	Mod	No	Mod	Low	Low	Mod	Low	High	Mod	Mod	Low	High	Low
22.	PS-710B	PE/TT	Low	Low	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Low	High-Mod	Low	High	Mod
23.	DZ-3	PE/TT	Low	Low	Mod	Yes	Mod	Low	Low	Low	Low	High	Low	Mod	Low	High	Low
24.	FX-5	PE/TT	Low	Low	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Low	Mod	Low	High	Mod
25.	FX-7	PE/TT	Low	Low	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Low	Mod	Low	High	Mod
26.	Echograph 1150	PE/TT	High	High	Low	Yes	Mod	Low	High	High	Mod	Mod	High	Mod-Low	High	High	Automated
27.	Echograph 1030	PE/TT	High	High	Mod	Yes	Mod	Low	Low	High	Mod	Mod	Low	Mod-Low	Mod	High	High
28.	Echograph 1030-QUASCO	PE/TT	Mod	Mod	Low	Yes	Mod	Low	Low	High	Mod	High	Low	Mod	Mod	High	High
29.	Echograph Series 10	PE/TT	Low	Low	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Low	Mod	Low	High	Mod
30.	Echograph Series 20	PE/TT	Low	Low	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Low	Mod	Low	High	Mod
31.	NovaScope 412	PE/TT	Mod	Mod	Mod	Yes	Mod	Low	Low	Mod	Mod	Mod	Mod	Mod	Low	High	High
32.	Epoch 2002	PE/TT	Mod	High	Mod	Yes	Mod	Low	Low	High	Mod	High	Low	Mod	Low	High	High
33.	5052 UA	PE/TT	Low	Low	Mod	Yes	Mod	Mod	Low	Low	Mod	High	Mod	Mod	Low	High	Mod
34.	5055 UA	PE/TT	Low	Low	Mod	Yes	Mod	Mod	Low	Low	Mod	High	Mod	Mod	Low	High	Mod
35.	Teneleven SG	PE/TT	Low	Low	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Low	Mod	Low	High	Low
36.	PA 1020	PE/TT	Mod	Mod	Mod	Yes	Mod	Low	Low	Mod	Mod	Mod	Low	Mod	Mod	High	Mod
37.	MIA 3000	Reson.	High	High	Mod	No	Mod	Low	Mod	Mod	Mod	Mod	Low	Mod		High	High
38.	USL 33	PE/TT	Low	Low	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Low	Mod	Low	High	Low
39.	USL 48	PE/TT	Mod	Mod	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Low	Mod	Low	High	Mod
40.	USM 3	PE/TT	Low	Low	Low	Yes	Mod	Low	Low	Low	Low	High	Low	Mod	Low	High	Low
41.	USM 35	PE/TT	Mod	Mod	Mod	Yes	Mod	Low	Low	Mod	Mod	High	Low	Mod	Low	High	Mod

(1) Pulse-Echo/Through-Transmission

(2) Acoustic-Ultrasonic

(3) Discontinued Production

*An explanation of the rating guidelines used in this table is contained in Appendix B.

(32 out of 41) are modular in construction to facilitate maintenance and repair. Also, the majority of the instruments (38 out of 41) are microprocessor-controlled and have interfaces for communication with an external computer and peripheral devices such as a printer, a video display, or a data storage device. Some of the computer-controlled instrumentation systems (15 out of 41) have capabilities for data acquisition, data processing, data analysis and evaluation, as well as documentation of the inspection. In general, microprocessor or computer-controlled instruments require a fair amount of operator training (2 weeks or more).

Portability of the instruments evaluated was generally high (28 out of 41). Also, about half of the instruments (23 out of 41) were battery operable (Low in the Power Requirement column in Table 1). The operating time of the batteries varied with each instrument but ranged typically from 6 to 12 hours.

III. LABORATORY TESTING OF SELECTED INSTRUMENTS

A. Instruments

During the Air Force program, four instruments were selected by the Air Force and evaluated in the laboratory. In accordance with the scope of work of the subject program, three out of these four instruments were evaluated in the laboratory in this program. The three instruments were:

- NDT Instrument, Inc. BondaScope 2100
- Sonatest UFD-S instrument
- Fokker B.V. Bondtester Model 80-L

The selection of these three instruments was made based on their good performance during the Air Force program.

The operating principles of the three selected instruments are described briefly in the following paragraphs.

1. BondaScope 2100

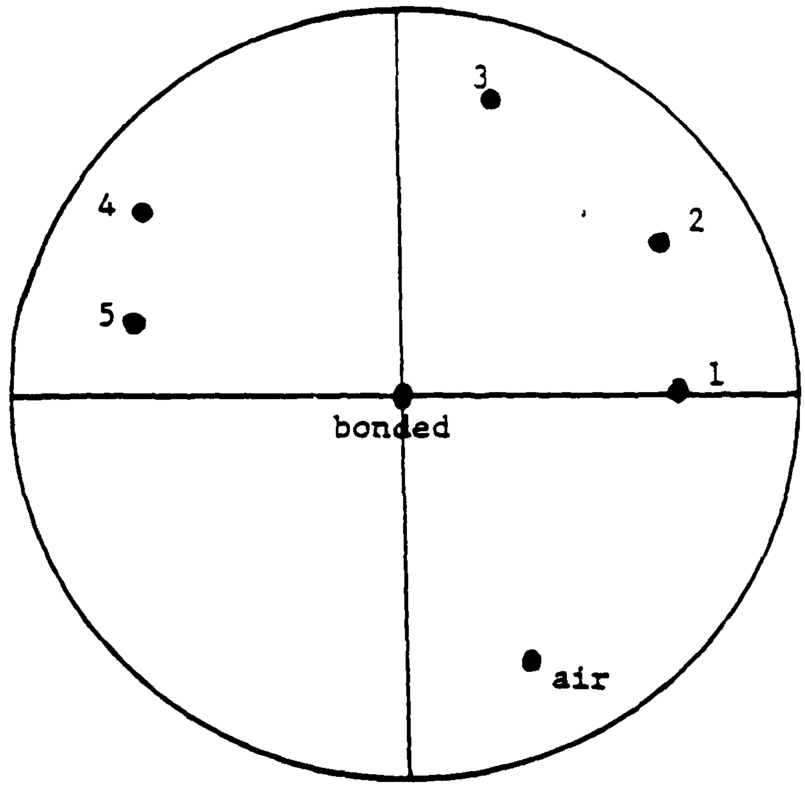
The BondaScope 2100 instrument operates on an ultrasonic principle, whereby the specific acoustic impedance of the material under test is monitored by electrical circuits sensitive to both the amplitude and the phase of the acoustic impedance. A piezoelectric transducer (or probe) is employed to transmit and receive the ultrasonic energy. The probe is excited by using a continuous wave (CW) of frequency equal to the resonant frequency of the piezoelectric crystal in the probe. Anomalies in the material such as debonds, delaminations, and voids create acoustic impedance changes which are detected, processed, and displayed as a "flying" dot on the instrument CRT.

When in use, the instrument is first calibrated or balanced on defect-free material. This calibration positions the dot at the center of the CRT screen. As the probe scans the test piece, the dot will displace from the center of the CRT when anomalies are encountered. The amount of displacement correlates with the changes in the amplitude and phase of the acoustic impedance of the material at that location. Figure 1 illustrates an example of the dot display obtained from a sample of multi-layered bonded laminate with unbonds (figure reproduced from the operating manual of the instrument). In this example, the dot was displaced from the center and moved counterclockwise with the increasing depth of the unbond from the surface of the sample. The position of the dot on the CRT display is used for flaw detection and characterization.

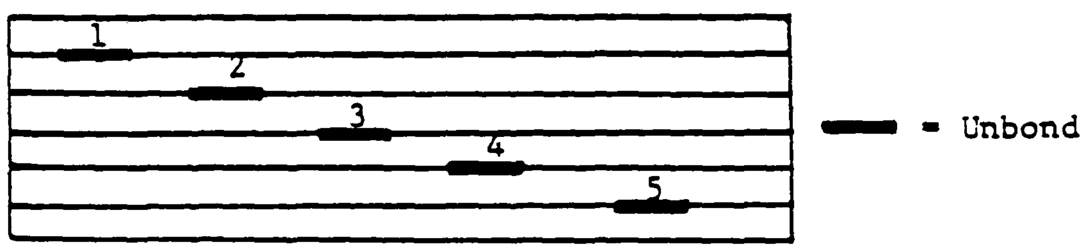
The instrument is operated with a contact type probe which requires a liquid couplant such as light machine oil on the test surface to transmit the ultrasonic energy through the contacting interfaces.

2. UFD-S Instrument

The UFD-S (ultrasonic flaw detector - shadow) instrument uses the shadow technique for flaw detection. The technique is similar to the ultrasonic



(a) BondaScope Display of Unbonds in Laminate Shown Below



(b) Multi-layered Bonded Laminate with Unbonds

Figure 1. BondaScope Ultrasonic Impedance Plane Presentation for a Multi-layered Laminate

pulse-echo or pitch-catch method except that it relies on the ultrasonic signal redirected by the presence of a defect rather than the direct reflected signal for flaw detection. Changes in the pattern of the received signal caused by defects are correlated to the condition of the material under test. More specifically, the following three factors are used for determining the material condition: (1) amplitude of the received signal, (2) displacement of the starting point of the first half-cycle of the received signal on the time base, and (3) shape of the interference pattern. Calibration of the instrument and probe alignment (distance between the transmitter and the receiver and their respective angle relative to the surface of a part under inspection) by using a reference sample of known condition is required prior to the inspection. Any changes in the signal pattern exceeding the predetermined acceptance level would indicate a fault or flawed condition. Figure 2 shows an example of signal pattern change with increasing fault condition (from the instrument brochure). Figure 2a is the signal from a good area. The received signal shown in Figure 2b is shifted to the right and is smaller in amplitude because of a fault condition (no specifics were given on the fault condition in the brochure). As the fault condition becomes more severe, the signal is shifted further to the right accompanied by a further reduction in amplitude as shown in Figure 2c. Two types of dry coupled probes are used with the instrument: a roller probe and a rubber-tip probe. Both probes do not require any liquid couplant. The roller probe is for continuous scanning. The rubber-tip probe is for intermittent spot checking.

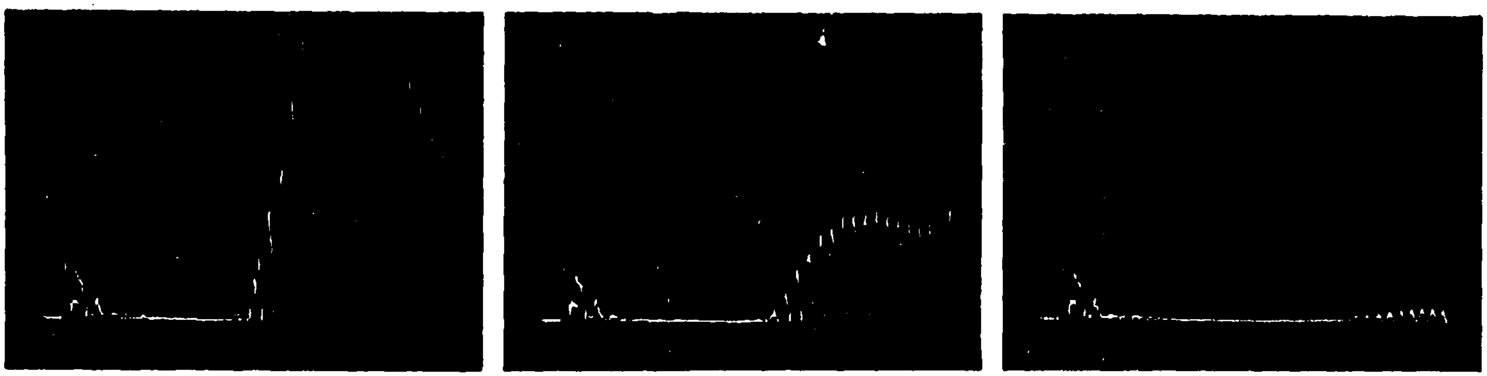
3. Fokker Bondtester Model 80-L

The Fokker Bondtester instrument is based on the principle that the resonant frequency and the electrical impedance of a piezoelectric crystal placed on the surface of a bonded structure are dependent on the quality of the bonded joints. The shift in resonant frequency and the change in electrical impedance of the crystal are measured and used for flaw detection and characterization. The instrument uses a continuous wave (CW) signal like the Bonda-Scope 2100 described above. To find the resonant frequency, however, the frequency of the CW signal is swept in a certain range determined by the setting on the instrument. When the applied CW frequency equals the resonant frequency of the crystal, the electrical impedance of the crystal exhibits the most change. Both the shift in resonant frequency (called A-Scale) and the peak change in electrical impedance (called B-Scale) are displayed on the instrument. Since the instrument relies on relative changes, it must be calibrated prior to the inspection by using a reference sample. An example of typical A-Scale indications for various bond qualities is illustrated in Figure 3 (from the operating manual of the instrument).

The crystals (or probes) used with the instrument require a liquid couplant.

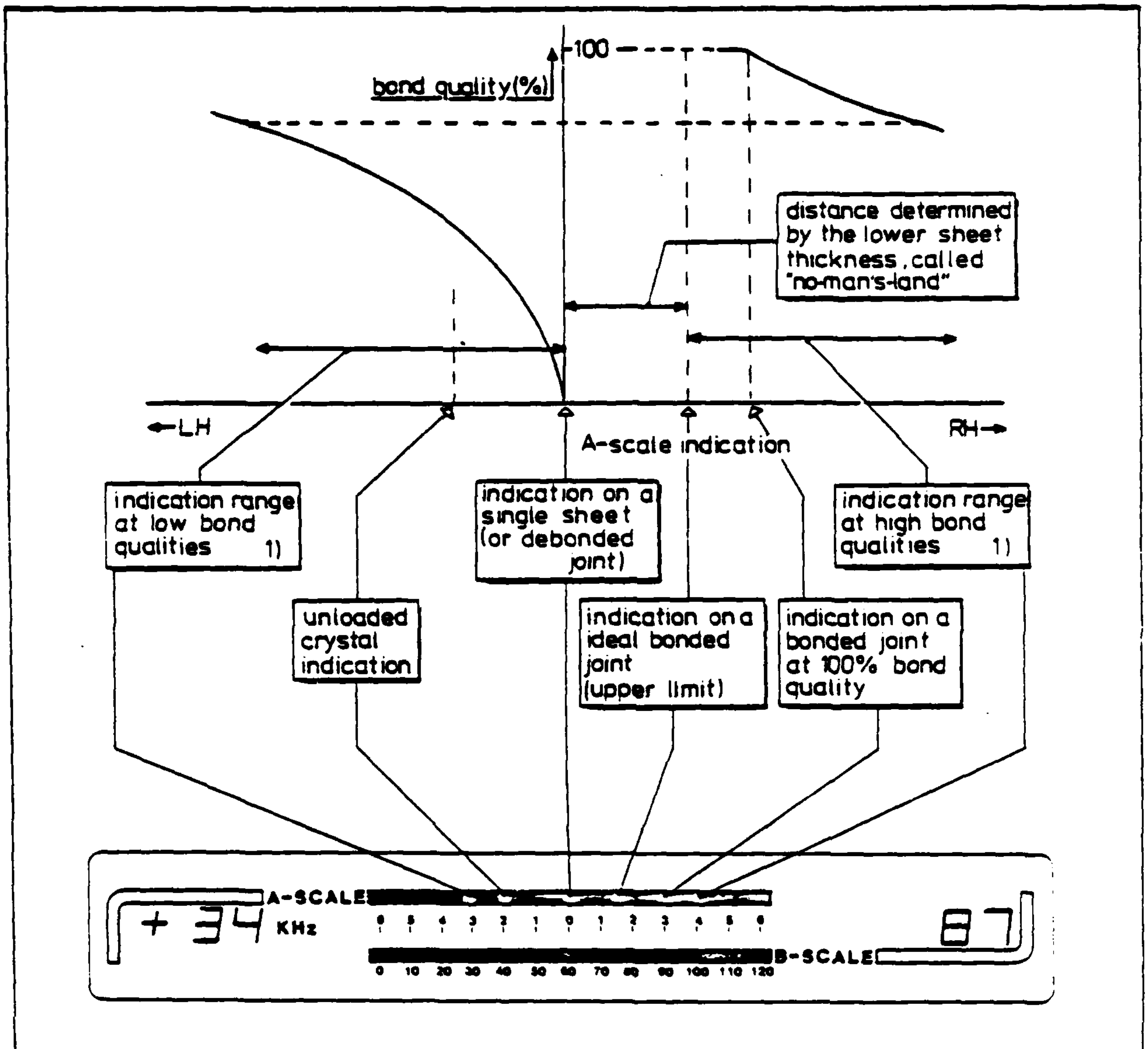
B. Specimens

Ten specimens of Army composite airframe structures were used in the laboratory testing. Figure 4 is a photograph of the samples. The samples were provided by the Army and were of unknown characteristics and defect conditions. The size, thickness, and description of the specimens used are given in Table 2.



(a) Good Area (b) Faulted Area (c) More Faulted Area

Figure 2. Example of Changes in the UFD-S Signal Pattern With Increasing Fault Condition



1) Only one arbitrary LED-bar indication is shown.

Figure 3. Typical Bondtester A-Scale Indications on a Single Bondline Configuration with Relatively Thin Lower Sheets as a Function of Bond Quality

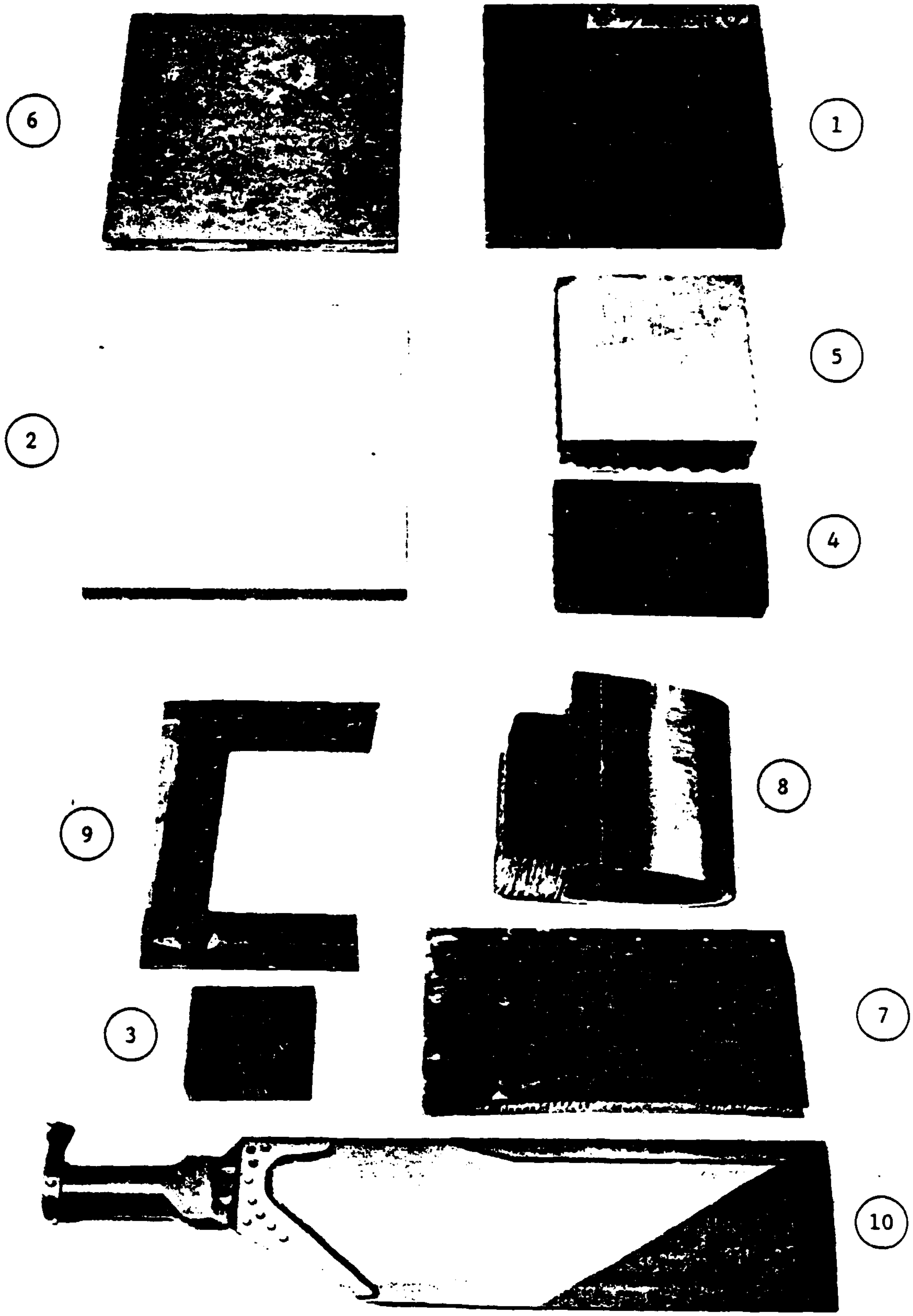


Figure 4. Composite Airframe Structure Specimens Used in the Laboratory Testing

Table 2

SIZE, THICKNESS, AND DESCRIPTION OF THE SPECIMENS USED

Specimen Number	Size (inches)	Thickness (inches)	Description
1	10 x 10	1	Graphite epoxy skin, paper honeycomb panel
2	10 x 10	1	Fiberglass epoxy skin, paper honeycomb panel
3	4 x 4	1	Graphite epoxy skin, paper honeycomb panel
4	6.25 x 4	1	Graphite epoxy skin, paper honeycomb panel
5	6 x 6	2	Aluminum skin, honeycomb panel[(a)]
6	10 x 10	11/16	Aluminum skin, honeycomb panel[(b)]
7	12 x 7	3/4	Aluminum skin, aluminum honeycomb panel[(c)]
8	8 x 8	3 inch max.	Section of a helicopter blade edge
9	(d)	(d)	Piece of aluminum skin, aluminum honeycomb stiffened panel taken from an AH-1 helicopter
10	(e)	--	Helicopter tail rotor blade

(a) Nonmetallic honeycomb core of an unknown material type.

(b) The honeycomb was not visible because the sides of the specimen were sealed with a sealant.

(c) The top and bottom surfaces of the specimen were rough. The top surface (shown in Figure 4) had wrinkles in an irregular fashion. The bottom surface was embossed in a diamond shape pattern.

(d) About 11 inches wide. Each leg of the specimen was approximately 5 inches long and 2 inches wide. The specimen leg was stiffened with honeycomb stringer approximately 0.25 inches high, 0.5 inches wide, and 4.5 inches long.

(e) Approximately 24 inches long; the blade section was 5.25 inches wide.

C. Testing Procedure

Prior to the inspection with the three selected instruments, both the top and bottom surfaces of each specimen were grid marked. The size of the grid was 0.75 x 0.75 inch for all the specimens except specimen 10 on which a 1 x 0.75 inch grid was marked.

Normally, the instruments need to be calibrated using reference samples of known characteristics. The specimens used in this testing, however, had unknown characteristics and unknown presence of flaws, if any. Therefore, normal instrument calibration procedures could not be used. As an alternative, the following procedures were used to calibrate the instruments.

(1) Place a probe on the specimen and display the resulting signals.

(2) Null or adjust the instrument according to the operating manual by treating the detected signal as a reference signal.

(3) Scan the specimen and observe the variations in the signal. Note the typical responsr from the majority of the areas on the specimen.

(4) Move the probe to a location producing the typical response obtained in step (3). Renull or readjust the instrument.

The instrument was calibrated for each specimen and recalibrated whenever either the probe was changed, the inspection was moved to the opposite surface of the specimen (from top to bottom or vice versa), or a significant variation in the specimen configuration produced a large variation in the signal response. For the latest case, the inspection surface of the specimen was divided into several sections so that each section had a roughly uniform structural configuration. The instrument was recalibrated for each such section.

After the instrument was calibrated, the probe was placed at each of the grid node points marked on the specimen and the resulting signal was evaluated. If the signal thus obtained was significantly different from the signal used for calibrating the instrument, then that location was recorded as a defective area. Roughly two times the magnitude of the normal variation in the signal was used as the threshold level for a flaw indication.

Five probes (two each for the Fokker Bondtester 80-L and BondaScope 2100 and one for the UFD-S instrument) were used in the laboratory testing. The type, frequency, and diameter of each of the probes used are described in Table 3.

D. Results

The locations of flaw indications found from both the top and bottom surfaces of each of the specimens are shown in Figures 5 through 13. The instrument and probe combination used for finding a specific flaw location is indicated by using the five different symbols illustrated in the figures.

Table 3

DESCRIPTION OF THE PROBES USED IN THE LABORATORY TESTING

Instrument	Probe Type	Probe Frequency	Probe Diameter (inch)
Fokker Bondtester	1414	Not Available*	1/4
80-L	3814	Not Available*	
BondaScope 2100	L2	260 - 300 kHz	1/4
	L6	355 - 385 kHz	1/8
UFD-S	Wheel (Roller)	1.25 MHz	1

*Approximately 350 kHz.

On specimen 1 (graphite epoxy skin, paper honeycomb structure, 10 x 10 x 1 inches), four flaw locations were found as illustrated in Figure 5. One location (M-11 on the top surface) was detected with both the Fokker Bondtester Model 80-L and the BondaScope 2100. The rest of the locations were detected with the Sonatest UFD-S.

On specimen 2 (fiberglass epoxy skin, paper honeycomb structure, 10 x 10 x 1 inches), two flaw locations were detected on the top surface as described in Figure 6. These locations were found with the Fokker Bondtester Model 80-L and the 3814 probe combination only. No flaw indications were detected with the other combinations of the instrument and probe.

Locations of flaw indications found on specimen 3 (graphite epoxy skin, paper honeycomb structure, 4 x 4 x 1 inches) are illustrated in Figure 7. They were observed at 13 locations on the top surface and 4 locations on the bottom surface. Nine locations exhibited flaw indications by more than one instrument-probe combination: eight (locations C-1, C-2, C-5, D-1, D-2, E-1, E-4, and E-5) on the top surface and one (location E-4) on the bottom surface of the specimen.

Locations of flaw indications found on specimen 4 (graphite epoxy skin, paper honeycomb structure, 6.25 x 4 x 1 inches) are shown in Figure 8. Of the six locations detected on the top surface, two (locations C-2 and C-8) showed flaw indications by more than one instrument-probe combination. No flaw indications were observed with the UFD-S instrument on the top surface of the specimen. On the bottom surface, a total of 18 locations exhibited flaw indications; of these, only two locations (C-2 and C-6) were found with more than one instrument-probe combination. Most of the flaw indications on the bottom surface were detected with the UFD-S instrument.

Figure 9 shows the locations of flaw indications found on specimen 5 (aluminum skin, honeycomb structure, 6 x 6 x 2 inches). A total of 13 flaw indications were found on the top surface; of these, five (locations A-7, C-5,

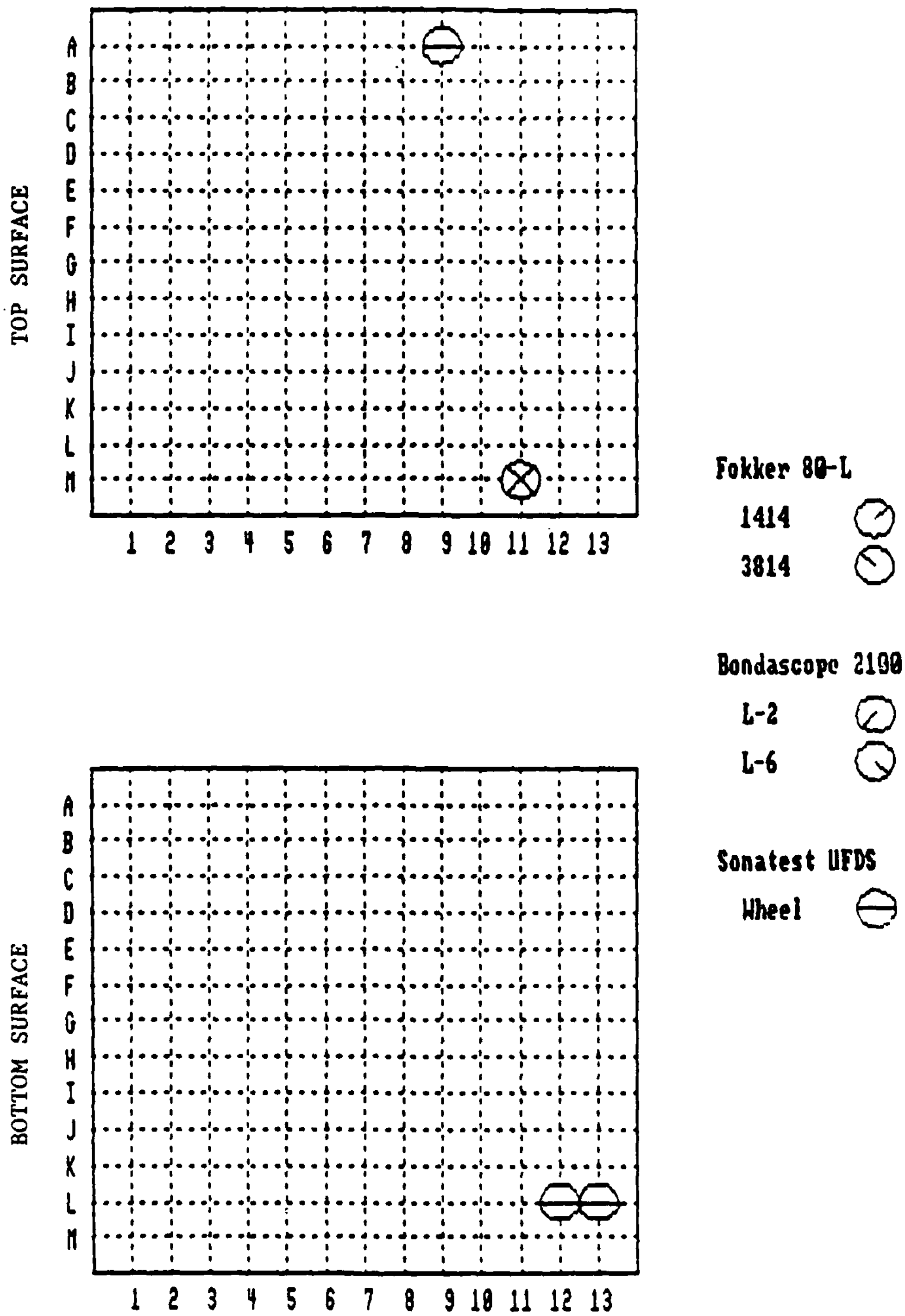


Figure 5. Locations of Flaw Indications Found on Specimen 1 (Graphite Epoxy Skin, Paper Honeycomb Structure)

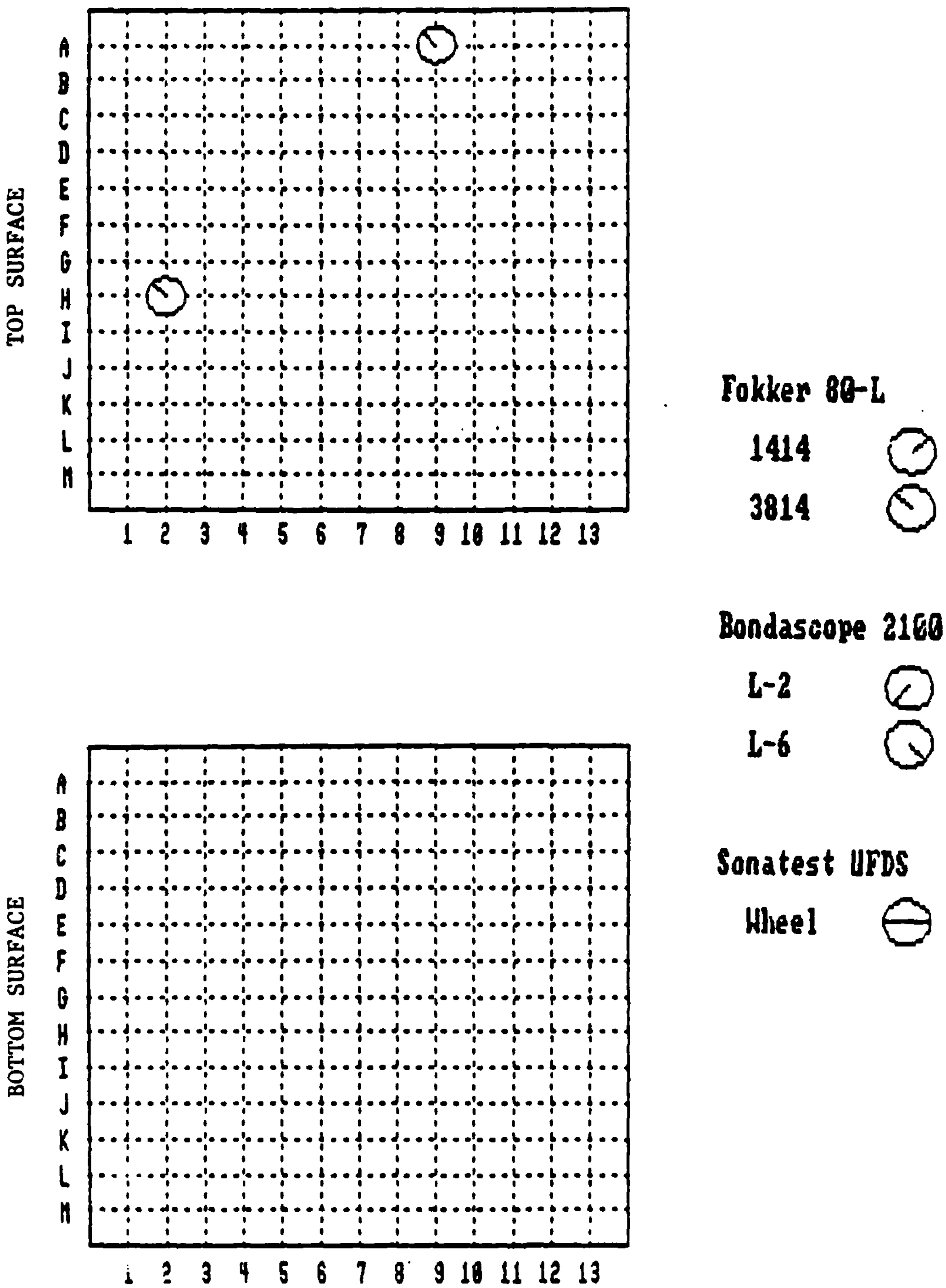


Figure 6. Locations of Flaw Indications Found on Specimen 2 (Fiberglass Epoxy Skin, Paper Honeycomb Structure)

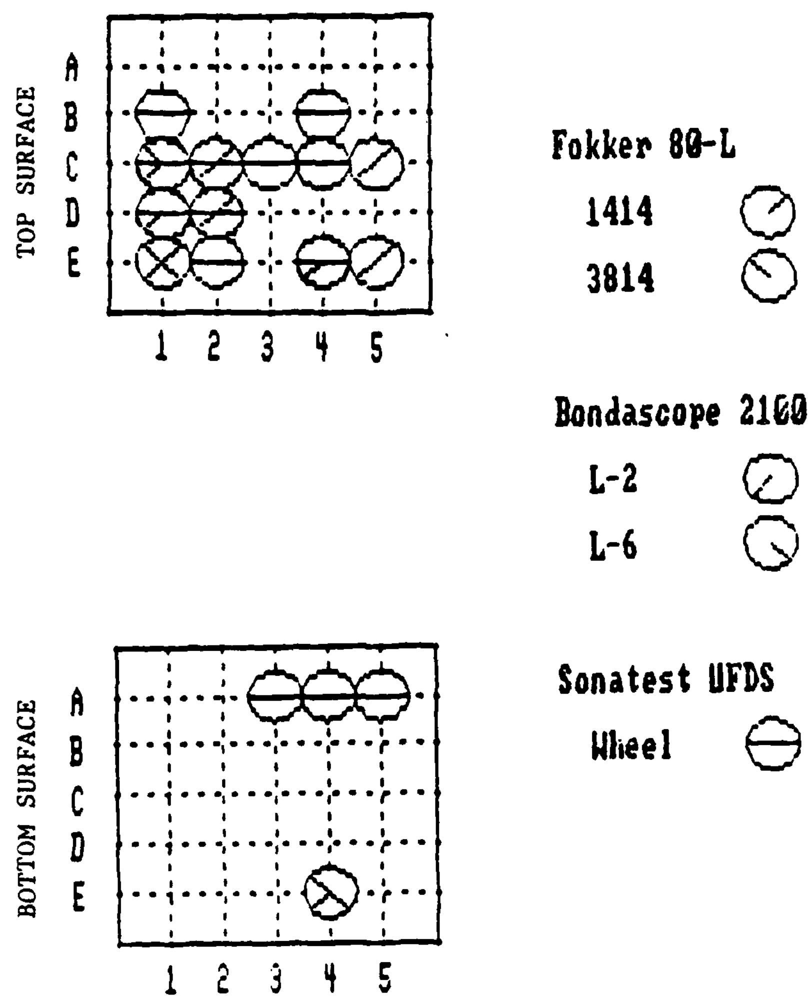


Figure 7. Locations of Flaw Indications Found on Specimen 3 (Graphite Epoxy Skin, Paper Honeycomb Structure)

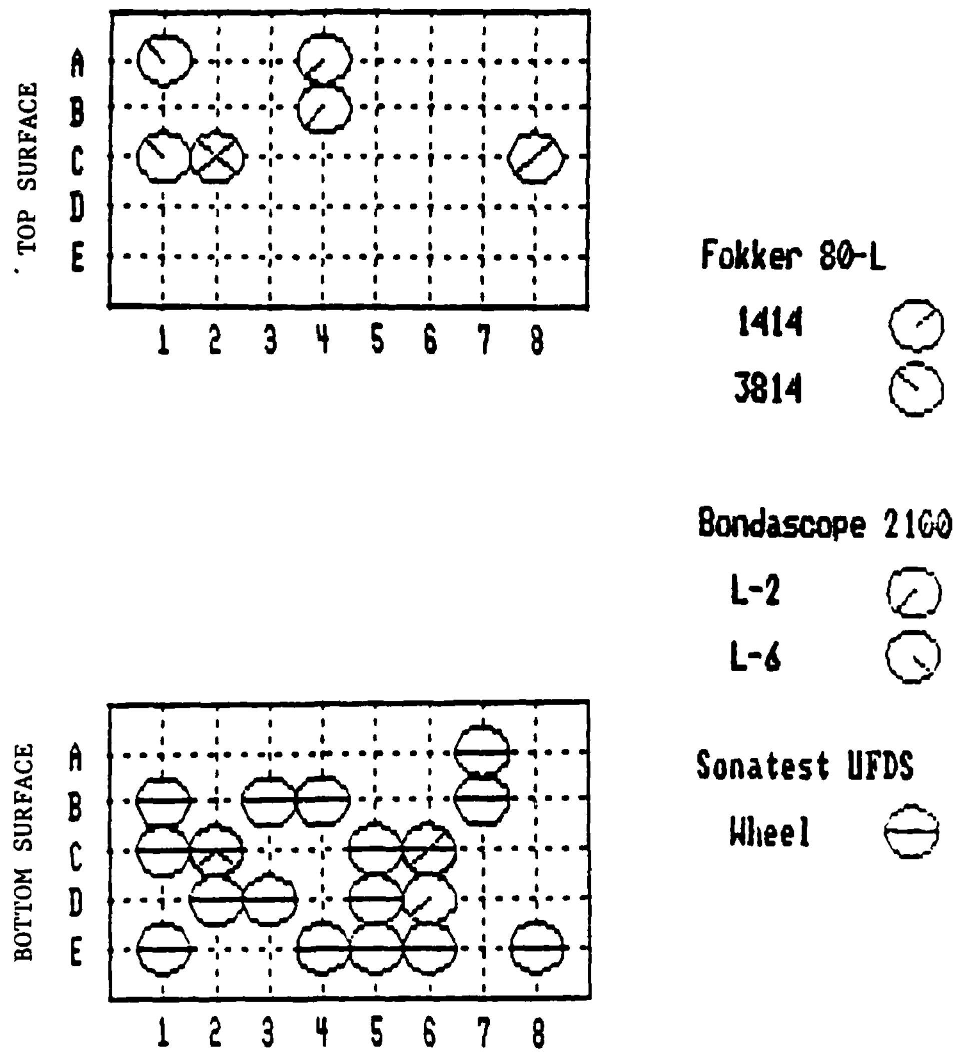


Figure 8. Locations of Flaw Indications Found on Specimen 4 (Graphite Epoxy Skin, Paper Honeycomb Structure)

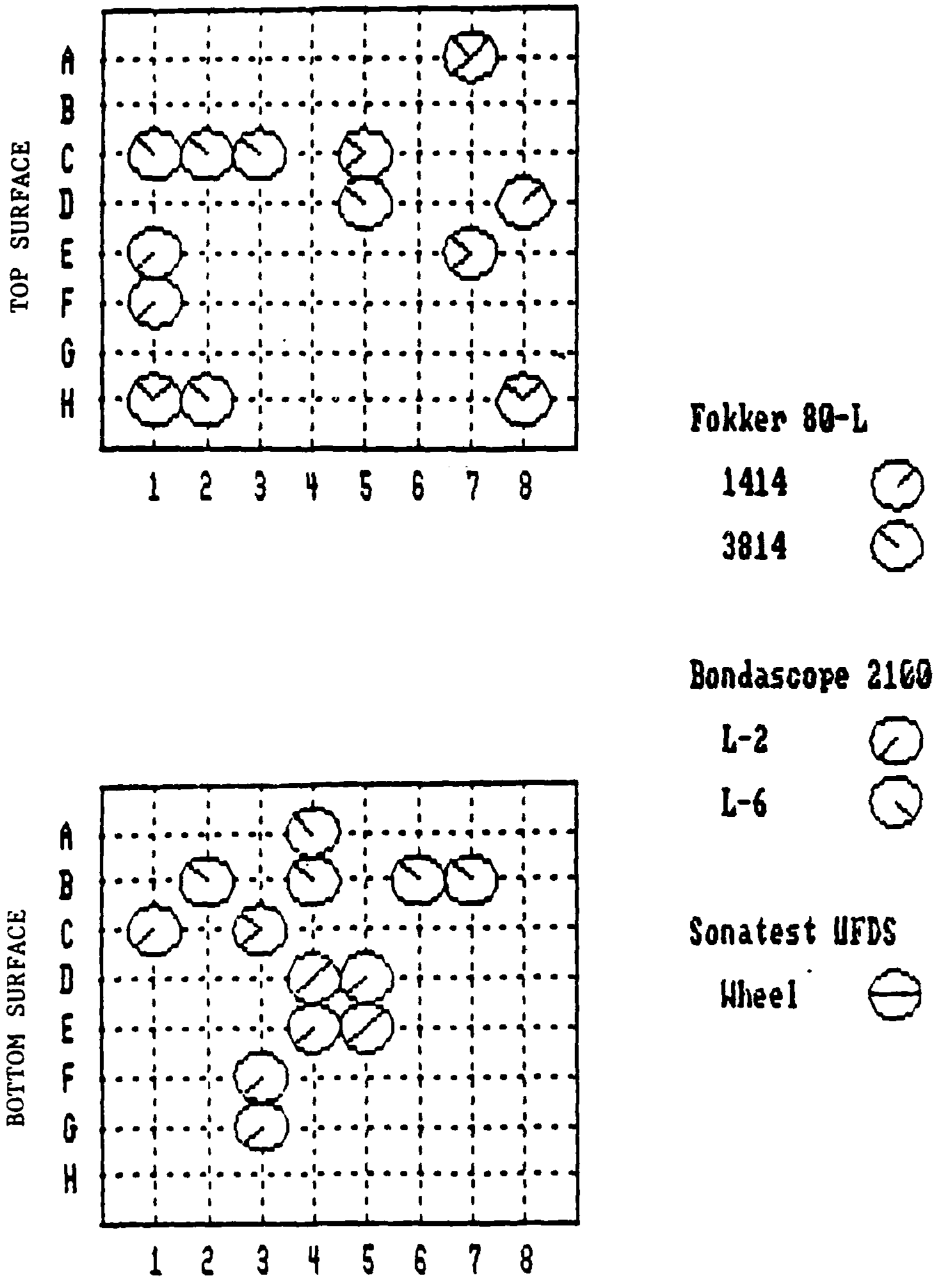


Figure 9. Locations of Flaw Indications Found on Specimen 5 (Aluminum Skin, Honeycomb Structure)

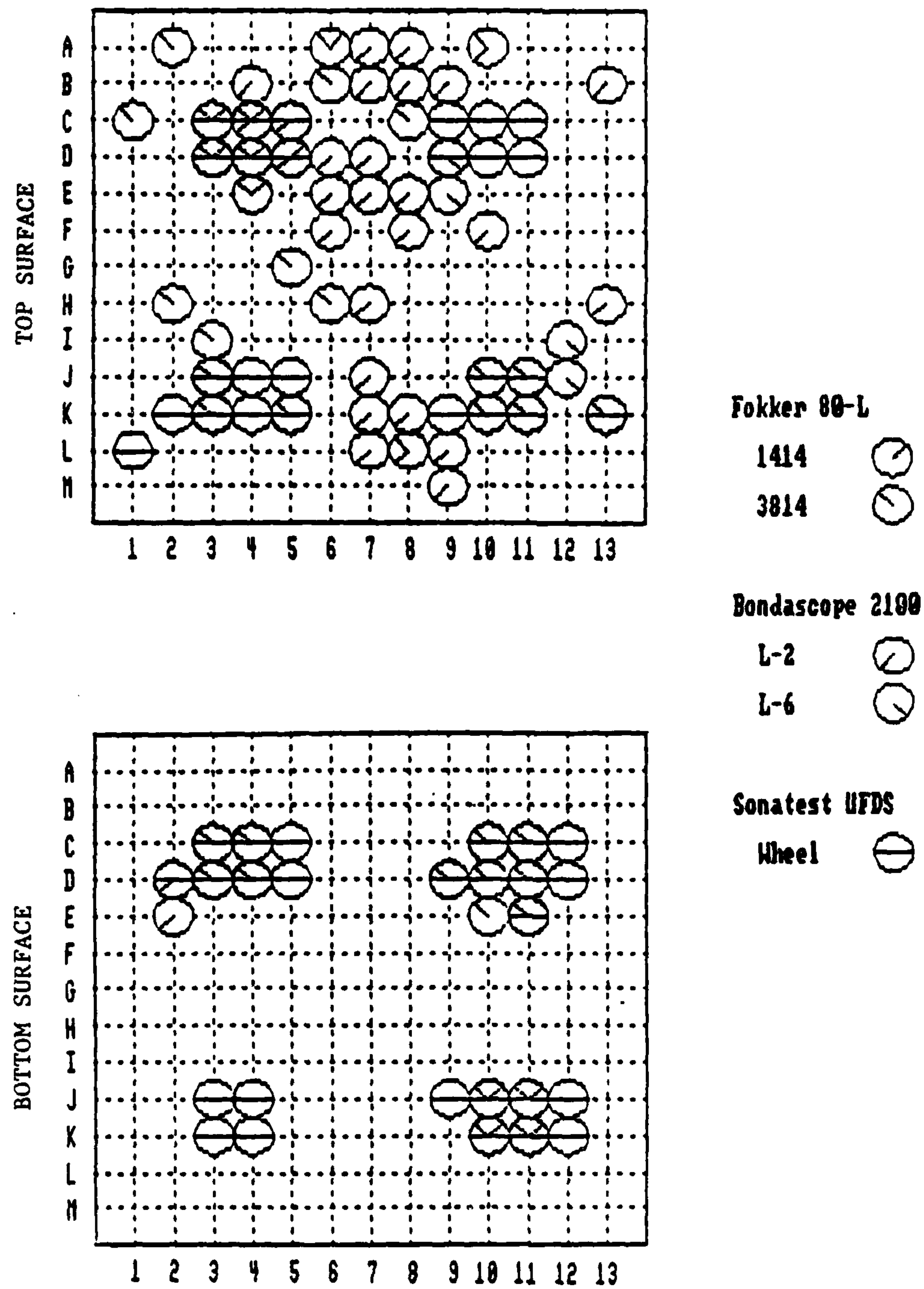


Figure 10. Locations of Flaw Indications Found on Specimen 6 (Aluminum Skin, Honeycomb Structure)

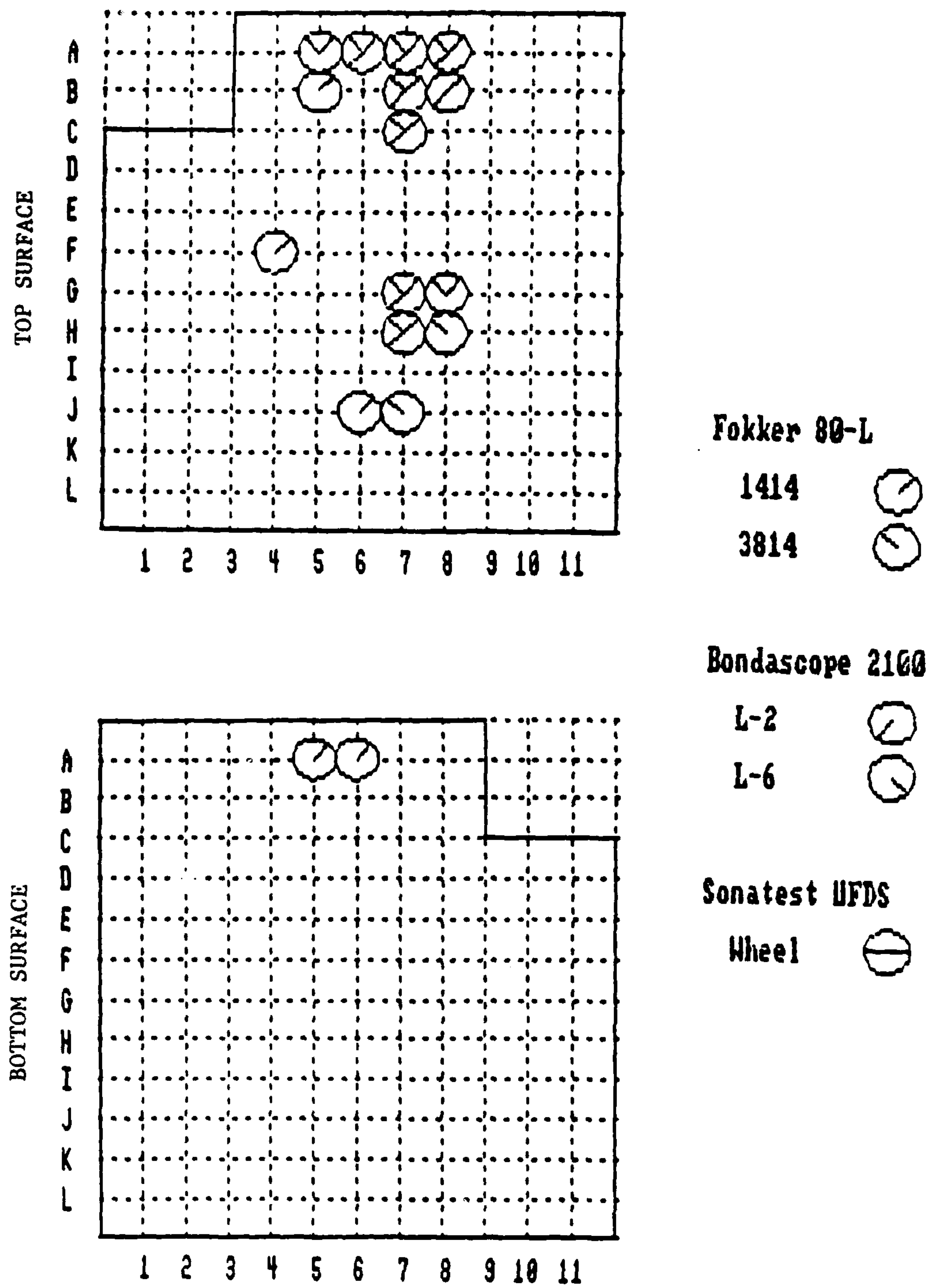


Figure 11. Locations of Flaw Indications Found on Specimen 8 (Section of Helicopter Blade Leading Edge)

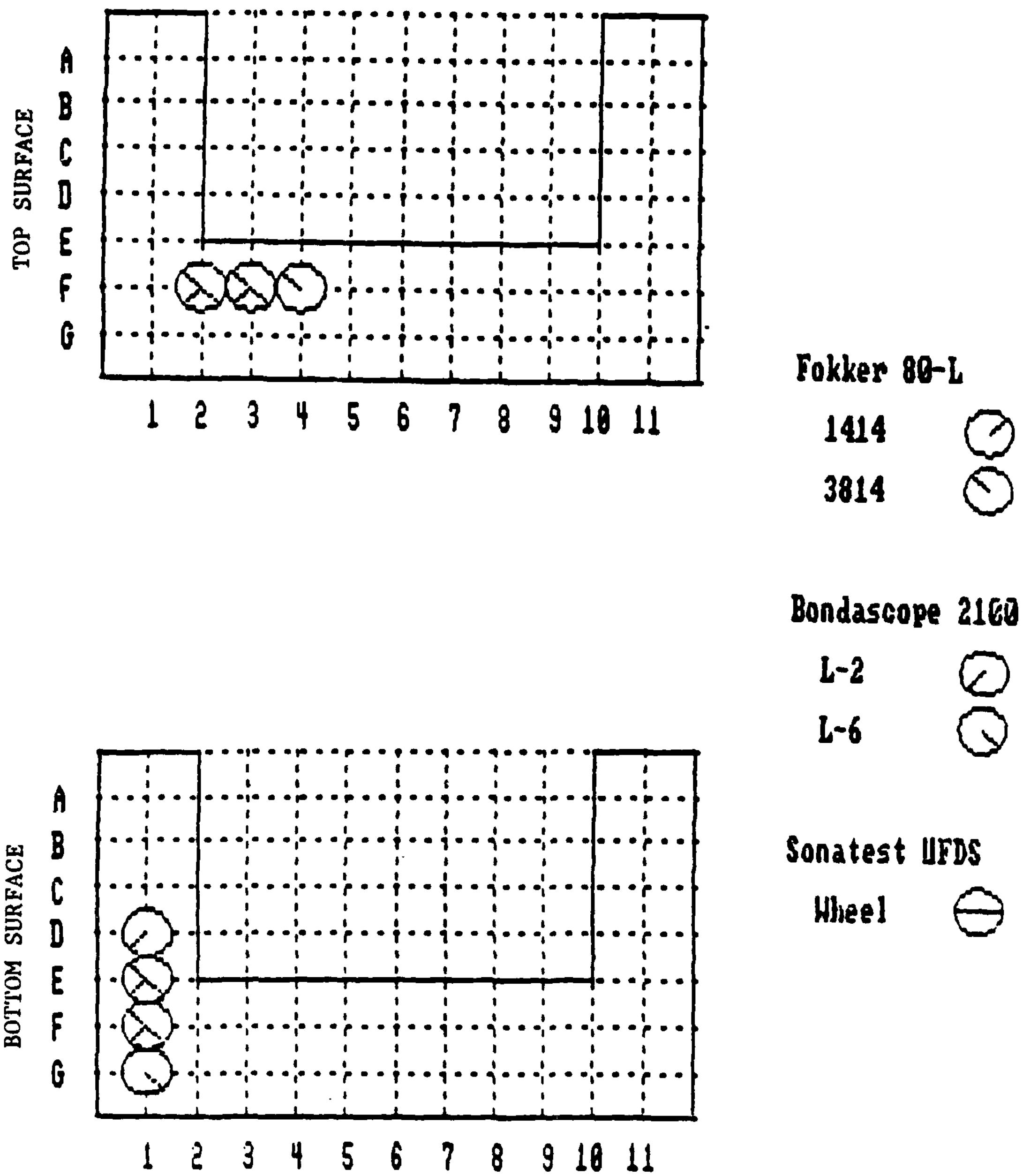


Figure 12. Locations of Flaw Indications Found on Specimen 9 (Piece of Aluminum Skin, Aluminum Honeycomb Stiffened Panel)

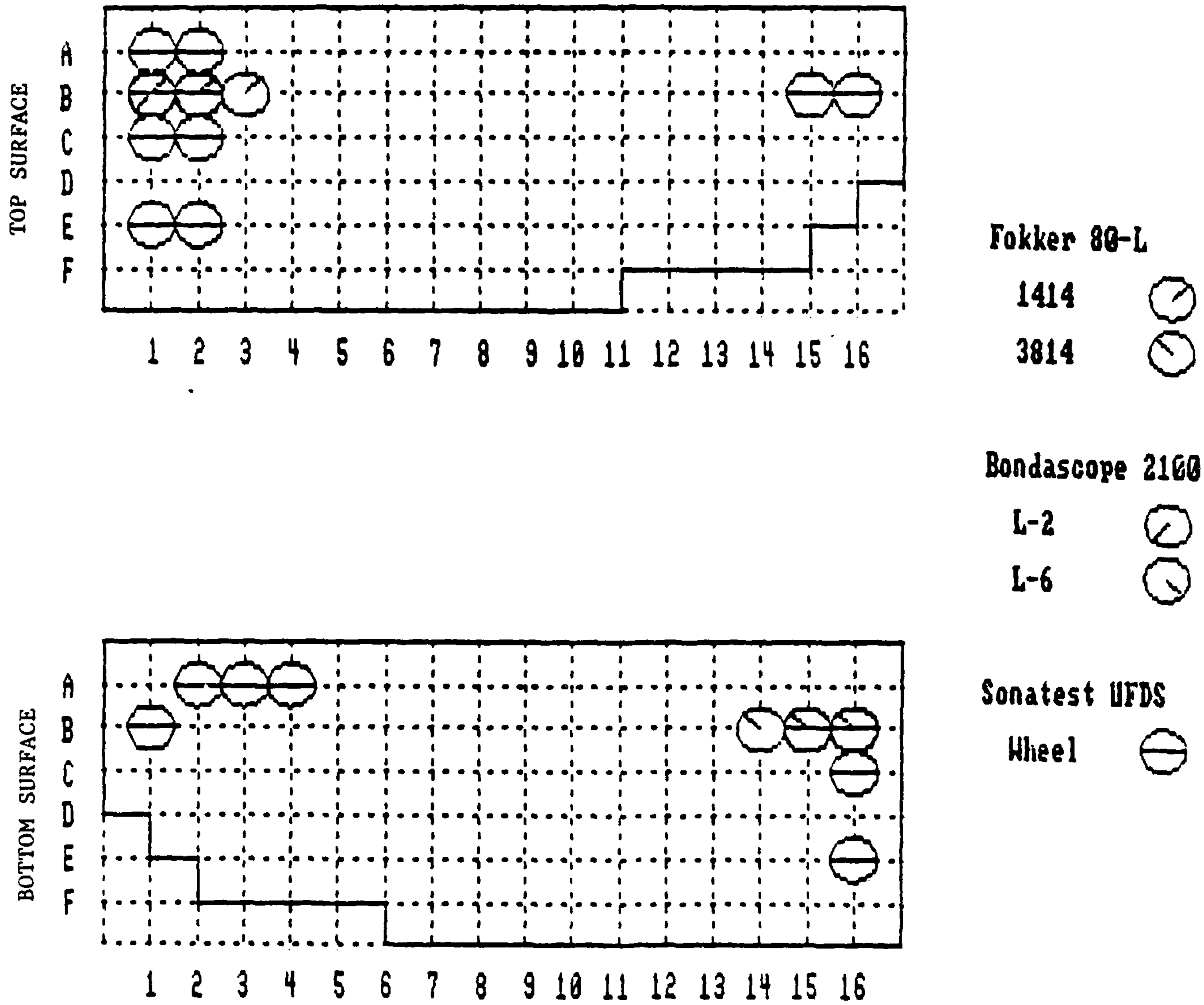


Figure 13. Locations of Flaw Indications Found on Specimen 10 (Helicopter Tail Rotor Blade)

E-7, H-1, and H-8) were detected with more than one instrument-probe combination. On the bottom surface, 13 flaw indications were also found; of these, three (locations C-3, D-4, and E-5) were detected with more than one instrument-probe combination. The locations of flaw indications shown in Figure 9 were found by using the Fokker Bondtester Model 80-L and BondaScope 2100. No indications were detected with the UFD-S instrument because of too much signal variations and resulting difficulty in calibrating the instrument.

Figure 10 shows the locations of flaw indications found on specimen 6 (aluminum skin, honeycomb structure, 10 x 10 x 11/16 inches). On the top surface, a total of 64 locations showed flaw indications; 19 of these were detected with more than one instrument-probe combination. On the bottom surface, a total of 28 locations showed flaw indications; 15 of these were detected with more than one instrument-probe combination.

On specimen 7 (aluminum skin, aluminum honeycomb structure, 12 x 7 x 3/4 inches), no meaningful flaw locations were detectable with the instruments used. Because of the rough surface conditions of the specimen, it was very difficult to make and maintain proper coupling of the probe to the specimen. Consequently, the signal varied widely and it was very difficult to calibrate the instruments and to discern flaw indications.

Figure 11 shows the locations of flaw indications found on specimen 8 (a section of helicopter blade leading edge). Because of the change in the curvature on the surface and the change in the thickness, recalibration of the instruments was required for inspecting different regions of the specimen. On the top surface, 15 locations of flaw indications were found with the Fokker Bondtester Model 80-L and the BondaScope 2100. No flaw indications were found with the UFD-S instrument. Of these locations, 10 exhibited flaw indications for more than one instrument-probe combination. On the bottom surface, only two locations showed flaw indications which were detected with the Fokker Bondtester Model 80-L and probe 1414 combination. The surface curvature in the area where columns 9 through 11 were marked was too large to maintain a proper coupling of the probes for the Fokker Bondtester Model 80-L and the BondaScope 2100. Therefore, the area was not inspectable with the Fokker Bondtester and the BondaScope.

Figure 12 shows the locations of flaw indications found on specimen 9 (a cutout piece of corroded aluminum skin, aluminum honeycomb stiffened panel). As shown, three locations on the top surface and four locations on the bottom surface were detected with the Fokker Bondtester Model 80-L and the BondaScope. The specimen was not inspectable with the UFD-S instrument because the wheel probe was too large for scanning the specimen and the instrument was difficult to calibrate.

Figure 13 shows the locations of flaw indications found on specimen 10 (a helicopter tail rotor blade). Because of the change in specimen configuration, recalibration of the instruments was required for each row marked on the specimen. A total of 11 locations on the top surface and 9 locations on the bottom surface exhibited flaw indications. Most of these flaw indications were detected with the UFD-S instrument. With the BondaScope 2100, only one location (location B-1 on the top surface) exhibited a flaw indication. With the Fokker Bondtester Model 80-L, three locations were detected on each surface for a total of six locations. It was also observed that the painted area (dark area in the picture of specimen 10 shown in Figure 4) exhibited significantly different response from the unpainted area (bright area in the picture of the specimen shown in Figure 4) on both the Fokker Bondtester and the BondaScope 2100. This indicated that the paint on the specimen could significantly affect the instrument response. With the UFD-S instrument, no significant difference in response was observed between the painted and unpainted areas.

E. Discussion

Generally speaking, calibration and operation training for both the Fokker Bondtester Model 80-L and the BondaScope 2100 can be accomplished within a few hours. Both instruments were sensitive to the variation in the coupling state between the probe and the specimen. Both instruments were designed for spot checking and therefore inspections with these instruments were slow.

On the other hand, the UFD-S instrument was difficult to calibrate, particularly in the absence of reference samples of known characteristics. Therefore, the operator must have extensive experience in calibration and operation of the instrument. The wheel (or roller) probe allowed continuous scanning of the specimen and consequently the inspection could be done within a short time. The fixture for holding the two wheel probes (one for transmitting and the other for receiving) in place, which was provided to us with the instrument for the laboratory evaluation, did not hold the probes well and thus needed further improvement.

Locations of flaw indications found on the specimen varied depending on the instrument-probe combination employed. The fact that only a small percentage of the flaw indications found was detected with more than one instrument-probe combination suggests that each instrument-probe combination has different sensitivity and/or different areas of application. To evaluate the accuracy and flaw sensitivity of each of the five instrument-probe combinations used in the laboratory testing, detailed characterization of the specimens is required, perhaps using other NDE techniques such as ultrasonic C-scan, x-ray, or neutron radiography, or destructive sectioning. Characterization of the flaws in these specimens was beyond the scope of the present program.

All three instruments were difficult to use for inspection of specimen 7, which had a rough surface. This indicates that their applicability is limited to parts having smooth surfaces. In addition, surface curvature was found to limit the applicability of both the Fokker Bondtester and the BondaScope. The paint on the specimen significantly affected the response of both the Fokker Bondtester Model 80-L and the BondaScope, indicating that variations in paint thickness may limit the accuracy of these instruments.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

Instruments Available

(1) More than fifty commercial ultrasonic instruments are available for nondestructive inspection of bonded aircraft structures. (See Appendix A for a list of 58 such instruments.) The majority of these instruments are conventional ultrasonic flaw detectors based on pulse-echo and through-transmission techniques. The rest of the instruments, which comprise a small minority, are based on nonconventional techniques including the resonance technique, the shadow technique, and the acousto-ultrasonic technique.

Literature Evaluation

(2) Most of the 41 instruments evaluated in this study use sensors (or probes) which require a liquid couplant such as light machine oil or water to transmit ultrasonic energy through the contacting interfaces between the probe and the part under inspection. Several instruments are operated with dry-coupled probes which do not require a liquid couplant. The dry-coupled probes use a pliable and resilient material such as rubber to transfer ultrasonic energy from the piezoelectric crystal to the part under inspection and vice versa. The degree of coupling of both the liquid-coupled and dry-coupled probes influences the inspection results. Therefore, to obtain repeatable results, uniform and consistent coupling of the probes is required.

(3) The trend in ultrasonic instruments is toward digital, automatic, and computer-controlled instruments. The majority of the commercial instruments are microprocessor-controlled with interfaces for communication with other devices such as an external computer, a printer, a recorder, or a video display. Also, the majority of the instruments are modular in construction to facilitate maintenance and repair. In addition, almost all instruments are equipped with visual and/or audible alarms to aid in flaw detection.

(4) Almost all the instruments evaluated require a smooth and clean surface of the part for inspection. However, substantial surface preparation such as removing paint on the part is not generally required. In addition, most of the instruments are operable in field environmental conditions. Except for highly sophisticated and automatic instruments and some instruments operated with a wheel type probe, the inspection speeds of the instruments are generally slow. The portability of the instruments is generally high. Also, about 50% of the instruments are battery operable. The operating time of the batteries varies with each instrument but ranges typically from 6 to 12 hours. The equipment cost varies over a wide range from several thousand dollars to over a quarter of million dollars depending on the degree of sophistication and automation.

Laboratory Evaluation

(5) Three instruments, the Fokker Bondtester Model 80-L, BondaScope 2100, and UFD-S, were evaluated in the laboratory using a total of ten specimens

of composite airframe structures supplied by the U.S. Army. The specimens had unknown characteristics and flaw conditions. Based on observations made during the laboratory testing, the following conclusions can be drawn:

(a) Both the Fokker Bondtester Model 80-L and the BondaScope 2100 were easy to calibrate and easy to use, whereas the UFD-S instrument was difficult to set up and calibrate without the use of reference samples of known characteristics.

(b) Both the Fokker Bondtester and the BondaScope were designed for spot checking, whereas the UFD-S instrument allowed continuous scanning of the specimen.

(c) Probes for both the Fokker Bondtester and the BondaScope are coupled to the specimen with a liquid couplant, while the wheel probe for the UFD-S instrument does not require any liquid couplant.

(d) All three instruments were limited to inspection of smooth-surfaced specimens.

(e) Both the Fokker Bondtester and the BondaScope were difficult to use on a highly curved surface. This limitation is due to the difficulty in maintaining proper coupling of the probe to the curved surface.

(f) Variations in paint thickness might limit the accuracy of the inspection results.

(g) All three instruments are suitable for routine field inspection of composite airframe structures.

(h) Because the specimens used had unknown characteristics and flaw conditions, the accuracy and flaw sensitivity of the three instruments could not be evaluated.

B. Recommendations

(1) Characterization of the specimens using independent methods is recommended in order to evaluate the accuracy and flaw sensitivity of the three instruments.

(2) Because of the availability of improved ultrasonic equipment, evaluation of the ultrasonic inspection equipment currently used in the Army is recommended to determine the need for upgrading equipment to better achieve the Army's aircraft maintenance goals.

APPENDIX A

A LISTING OF NAMES AND MANUFACTURERS OF ULTRASONIC INSTRUMENTS FOR INSPECTION OF BONDED STRUCTURES*

*The listing contained in this Appendix was generated during the literature evaluation performed under the Air Force program (see Paragraph I.B and Section II).

No.	Equipment Name	Manufacturer
1.	Ultra Image III	Ultra Image International
2.	Acousto-Ultrasonics Instrumentation System	Physical Acoustics Corp.
3.	Multisonic/PC	California Data Corp.
4.	UFD-S Ultrasonic Flaw Detector	Sonatest
5.	Zipscan 2	SGS Sonomatic Ltd.
6.	Sparta TTU-90	Sparta Technology
7.	USIP 12 Ultrasonic Flaw Detector	Krautkramer Branson
8.	USIP 11 Ultrasonic Flaw Detector	Krautkramer Branson
9.	PARIS (Portable Automated Remote Inspection System)	Sigma Research, Inc.
10.	SDL-1000 Ultrasonic Imaging System	Sigma Research, Inc.
11.	Sigma Series 2000 Ultrasonic Imaging System	Sigma Research, Inc.
12.	USD-1	Krautkramer Branson
13.	Fokker Bondtester Model 80 L	Fokker B.V.
14.	M-Series Ultrasonic Instrument	Nortec/Metrotek
15.	NDT-132 Portable Ultrasonic NDT Instrument	Nortec/Metrotek
16.	AET Model 206AU Acousto-Ultrasonic Instrument	Acoustic Emission Technology Corp.
17.	NovaScope 3000	Automation/Sperry
18.	NovaScope 2000	Automation/Sperry
19.	BondaScope 2100	NDT Instruments, Inc.
20.	Bondtester 210	NDT Instruments, Inc.
21.	S-1A Sondicator Ultrasonic Test Instrument	Automation/Sperry

No.	Equipment Name	Manufacturer
22.	S-2B Sondicator Ultrasonic Test Instrument	Automation/Sperry
23.	PS-710B Pulse Ultrasonic Test Unit	Magnaflux Corp.
24.	FX-3 Ultrasonic Flaw Detector	Magnaflux Corp.
25.	FX-5 Ultrasonic Flaw Detector	Magnaflux Corp.
26.	FX-7 Ultrasonic Flaw Detector	Magnaflux Corp.
27.	Echograph 1150 Ultrasonic Instrument System	Karl Deutsch
28.	Echograph 1030 Portable Modular Ultrasonic Flaw Detector	Karl Deutsch
29.	Echograph 1030-QUASCO Portable Ultrasonic Quality Assurance System	Karl Deutsch
30.	Echograph Series 10 Portable Ultrasonic Flaw Detector	Karl Deutsch
31.	Echograph Series 20 Portable Ultrasonic Flaw Detector	Karl Deutsch
32.	Nanoscope 412 Ultrasonic Flaw Detector	Erdman Instruments Inc.
33.	Epoch 2002 Flaw Detector	Panametrics
34.	5052UA Ultrasonic Analyzer	Panametrics
35.	5055UA Ultrasonic Analyzer	Panametrics
36.	TenEleven SG Flaw Detector	Baugh & Weedon Ltd.
37.	PA1020 Ultrasonic Flaw Detector	Baugh & Weedon Ltd.
38.	MIA 3000 Structural Integrity Monitor	Inspection Instruments Ltd.
39.	USL 33 Ultrasonic Flaw Detector	Krautkramer Branson
40.	USL 48 Ultrasonic Flaw Detector Digital Thickness Instrument	Krautkramer Branson
41.	USM 3 Large Screen Ultrasonic Flaw Detector	Krautkramer Branson
42.	USM 3S Large Screen Ultrasonic Flaw Detector	Krautkramer Branson

No.	Equipment Name	Manufacturer
43.	Intraspect 98 Ultrasonic Imaging System	Combustion Engineering
44.	KB-6000 Ultrasonic Instrumentation System	Krautkramer Branson
45.	QC-2000 Reflectoscope	Automation/Sperry
46.	QC-400 Reflectoscope	Automation/Sperry
47.	M-90 Reflectoscope	Automation/Sperry
48.	S-80 Reflectoscope	Automation/Sperry
49.	CM 2000 Squirter Ultrasonic Scanning System	Custom Machine Inc.
50.	MBS-8000 Computer Controlled Ultrasonic Testing System	MATEC Instruments Inc.
51.	NDT-150 Ultrasonic Inspection System	Nortec/Metrotek
52.	NDT-131D Digital Ultrascope	Nortec/Metrotek
53.	1712A Computerized Ultrasonic Instrument	Systems Research Lab., Inc.
54.	AX-8000 Integrity Tester	American NDT, Inc.
55.	FD-700 Ultrasonic Flaw Detector	Mitsubishi Electric Corp.
56.	Mark IV Ultrasonic Flaw Detector	Sonic Instruments Inc.
57.	ARIS (Automated Realtime Inspection System)	Southwest Research Institute
58.	ABE (Advanced Bond Evaluator)	United Western Tech., Corp.

APPENDIX B

ULTRASONIC EQUIPMENT EVALUATION FORM AND RATING GUIDELINES*

*See Table 1.

ULTRASONIC EQUIPMENT EVALUATION FORM

Equipment Name :

Manufacturer :

Based on Thru-Transmission/Pulse-Echo Tech. ( ), Resonance Tech. ( )

- -

Maximum Output Voltage of the Pulser : Spike, Square Wave Pulse

Receiver Gain _____dB, Dynamic Range _____dB, Freq. Range ________MHz

Flaw Sensitivity :
Flaw Type : Delaminations, Voids, Unbonds/Debonds, Subsurface Damage
Flaw Location : Near Surface, Sub-surface
Flaw Size :

Accuracy in Locating a Flaw : Position ________, Depth __________

Dependency on Operator Skill :
Setup _________, Procedure __________, Interpretation _________

Need of Surface Preparation ________, Need of Couplant _________

Sensitivity to Environmental Conditions:
Temp._____, Humidity _____, Light _____, Shock and Vibration _______

Inspection Speed :

Repeatability/Reliability of Inspection Results :

Availability of Recorder Interface :

Cost of Inspection (Including supplies and consumables) :

Portability of Equipment :____________ Overall Weight _________

Maintainability of Equipment:
Modular Construction _________, Internal Diagnosis Capability __________

Power Requirement :

Personnel Safety :

Equipment Cost :

Ability to Automate :
Adaptation/Modification Cost for Automation :

Remarks

RATING GUIDELINES

1. Flaw Sensitivity

This rating pertains to the detectability of flaws of various types, sizes, and depths in a component. "Low" ratings refer to the case where the detectability is limited to flaws of a few specific types and a large size (1 inch or larger in diameter), and those located near the accessible surface. "High" ratings refer to the case where the detectability is good for various flaw types of small size (0.25 inch or smaller in diameter) throughout the thickness of the component. "Moderate" ratings are for the intermediate detectability.

2. Accuracy in Locating a Flaw

This rating pertains to the accuracy and the resolution in determining the spatial position of a flaw in a component.

3. Dependency on Operator Skill

This relates to the training and skill required by the operator to conduct the inspection. "Low" ratings refer to minimal training (two days or less) and technical knowledge (high school graduation or equivalent experience) requirements. "High" ratings refer to the case in which a two-week or more training and a high level of technical knowledge (university graduation or equivalent experience) are required. "Moderate" ratings are for those cases which require training and technical knowledge intermediate between the "Low" and "High" ratings.

4. Need of Surface Preparation

This rating measures the amount of surface preparation required in the region to be inspected. "Low" ratings refer to the case where little or no preparation is required other than wiping the surface to remove loose foreign material such as dirt. "Moderate" ratings refer to the case where all foreign material adhered to the surface such as grease,oil or dirt must be removed and a clean surface is required. "High" ratings refers to the case where a substantial surface preparation such as removing paint is required.

5. Sensitivity to Environmental Conditions

This relates to the influence of field environmental conditions (temperature, humidity, light, shock, vibration, and noise) on the operation of the equipment and performing the inspection. "Low" ratings refer to the case where the equipment is adequate for use in the field condition. "Moderate" is for the case where the equipment is marginal for use in the field condition. "High" is assigned to the equipment whose use is limited to the laboratory condition.

6. Inspection Speed

This relates to the speed of inspection. "Low" ratings are assigned if the inspection is done manually. "Moderate" ratings are assigned if the inspection is done manually with the use of a mechanical device such as yoke which facilitates the inspection. "High" ratings are assigned if the inspection is done by using a mechanical or electrical scanning device.

7. Repeatability/Reliability of Inspection Results

This rating pertains to the repeatability (or reproducibility) and the reliability of the inspection results. This is intended to identify the degree of variation in inspection results from day to day operation and from operator to operator. "Low" ratings are assigned if the inspection relies heavily on the subjective judgement of the operator and requires a high degree of operator interaction with the inspection process and operator's attention to detail. "Moderate" ratings are assigned if the equipment is provided with features such as visual or audible alarm to allow objective judgement of the operator and the dependence of the inspection results on the operator is low. "High" ratings are assigned if the equipment requires little or no operator's judgement.

8. Availability of Recorder Interface

This rating relates to the availability of outputs for recording inspection results such as amplitude, thickness, distance, or logic (yes or no; on or off) outputs. "Low" ratings are assigned if no recording output is available. "Moderate" ratings are assigned if any of the following outputs is available; amplitude, thickness, distance, or logic. "High" ratings are assigned if all of the above outputs and A-scan output are available.

9. Portability of Equipment

This relates to the easiness in transporting the equipment by hand. "High" ratings are assigned if the equipment is equal to or less than 30 lbs. "Low" ratings are assigned if the overall weight of the equipment is over 200 lbs or the equipment has a component weighing more than 50 lbs. "Moderate" ratings are assigned if the overall weight of the equipment is no more than 200 lbs and no component exceeds 50 lbs.

10 Maintainability of Equipment

This relates to the easiness in maintaining the equipment including repair and calibration. "High" ratings are assigned if the equipment consists of easily exchangeable plug-in modules or has internal diagnosis capability. "Moderate" ratings are assigned if the equipment can be diagnosed with standard testing device such as an oscilloscope and can be repaired and calibrated at user's facility in the Air Force. "Low" ratings are assigned if the equipment requires a special testing instrument or must be maintained at the manufacturer's facility.

11. Power Requirement

This rating measures the power required to operate the equipment and to conduct inspections. "Low" is assigned for power requirements which can be fullfilled with batteries. "Moderate" refers to a power requirement of a few hundred watts which could be obtained from a portable generator. "High" refers to a requirement of an electrical power line.

12. Personnel Safety

This rating measures the relative amount of precaution required in operating the equipment during the inspection to protect inspection personnel and other personnel nearby.

13. Equipment Cost

This rating pertains to the cost of the basic equipment excluding periperal equipment. "Low" is assigned if the equipment is equal to or less than $10,000. "Moderate" is assigned if the equipment is above $10,000 and equal to or less than $30,000. "High" is assigned if the equipment is above $30,000.

14. Ability to Automate

This rating refers to the capability of the equipment for automatic inspection. "Automated" is assigned if the equipment is already automated. "High" is assigned if the equipment is controllable using a microprocessor or a computer. "Moderate" is assigned if the equipment is manually controlled but can provide a digital output for data acquisition , process, and analysis using a computer. "Low" is assigned if the equipment is manually controlled and provides an analog output.

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EVALUATION OF BOND TESTING EQUIPMENT FOR INSPECTION OF ARMY ADVANCED COMPOSITE AIRFRAME STRUCTURES -
Hegeon Kwun and David G. Alcazar
Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78284

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Key Words

Adhesives
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Technical Report MTL TR 88-28, October 1988, 41 pp - illus-tables, Contract DLA 900-84-C-0910, Final Report

Forty-one ultrasonic bond testing instruments for nondestructive inspection of composite airframe structures were evaluated based on information available in the literature. In addition, three of these instruments, the Fokker Bondtester Model 80-L, the BondaScope 2100, and the Sonatest UFD-S, were evaluated in the laboratory using ten specimens of composite airframe structures supplied by the Army. All the specimens had unknown flaw conditions. Both the Fokker Bondtester and the BondaScope required only a few hours of operator training in calibration and operation. Both instruments require a liquid couplant and are used for spot checking. The UFD-S instrument was difficult to set up and calibrate without reference samples of known characteristics. Also, extensive operator training is required to calibrate and operate the UFD-S instrument. The UFD-S uses a wheel probe which does not require a liquid couplant and allows continuous scanning of the specimen. The inspection speed of the UFD-S was therefore much greater than that of the other two instruments. Surface roughness, surface curvature, and variations in paint thickness were observed to limit the applicability of the instruments. Although these instruments have certain limitations, they are suitable for routine field inspection of composite airframe structures.

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